

Vortex avalanches and self organized criticality in superconducting niobium

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In 1993 Tang proposed [1] that vortex avalanches should produce a self organized critical state in superconductors, but conclusive evidence for this has heretofore been lacking. In the present paper, we report extensive micro-Hall probe data from the vortex dynamics in superconducting niobium, where a broad distribution of avalanche sizes scaling as a power-law for more than two decades is found. The measurements are combined with magneto-optical imaging, and show that over a widely varying magnetic landscape the scaling behaviour does not change, hence establishing that the dynamics of superconducting vortices is a SOC phenomenon.

The concept of self-organized criticality (SOC), first proposed by Bak, Tang and Wiesenfeld [2], and then applied to many scenarios exhibiting avalanche dynamics [3,4] refers to the tendency of a system to endogenously self-organize into a critical state. An idealized sandpile is the prototypical example of a SOC system. As grains of sand are slowly added to the pile, it “organizes” itself by tuning the slope to a “critical” value, resulting in a marginally stable stationary state. Avalanches are scale invariant in a SOC system, and the distribution $P(s)$ of their size s follows a power law $s^{-\tau}$, where τ is a critical exponent. The value of τ is said to be universal in the sense that it should be robust to minor changes in the system.

Granularity, although of a different kind, is an inherent property also of type-II superconductors. When an external magnetic field is raised above a certain critical value, the material becomes a host for quantized magnetic vortices, which nucleate at the edges and are driven inwards by their mutual repulsion. In most materials this motion is impeded by microscopic defects acting as “pinning sites”, with the result that the vortices pile up with a characteristic density gradient, producing the so called “critical state” [5]. DeGennes first suggested as early as 1966 that avalanche dynamics could be also present in the superconducting critical state [6].

The possible development of SOC in type II superconductors plus the fact that the motion of vortices is overdamped, making them an ideal system in which to look for SOC behavior, has revived the interest in vortex avalanches in the last years, starting with the work of Field and coworkers [7]. In those experiments, and in similar ones performed by Heiden and Rochlin [8] vortex

avalanches were detected by means of large pick up coils in the center of Pb-In and Nb-Ti cylinders. However, with this experimental setup only the flux that leaves the superconductor is measured, and the amount of flux involved in each avalanche event can not be directly measured. Direct observation of avalanche dynamics with single vortex resolution is today possible using micro-Hall probes. With this technique Seidler et al. [9] found that avalanche-like behavior occurs at high fields and very low temperatures in YBaCuO crystals. The avalanche statistics, later worked out in [10], was quite limited being based on only a few hundred events. Nowak et al. [11] studied niobium thin films where the statistics was improved, although avalanche sizes below 50 vortices were absent. As pointed out by the authors, such films exhibit a thermo-magnetic instability, or catastrophic flux jumps, which may camouflage other basic dynamical features. This is consistent with the results by Esquinazi et al in thin Nb films [12]. Recently, much thicker niobium samples were investigated by Behnia et al. [13], who found only very small avalanches under the Hall probe area, leaving an open question whether the distribution is a power-law or stretched exponential. Until now no conclusive evidence has existed that the dynamics of magnetic vortices in superconductors is a genuine realization of SOC.

Local avalanche measurements are largely improved by first mapping out the global magnetic landscape in which the Hall probes are placed. Therefore, we made magneto-optical (MO) imaging of the flux penetration in our superconducting sample, a Nb foil of dimensions $1.5 \times 1.5 \times 0.25 \text{ mm}^3$, and carefully superimposed such images onto a picture taken afterwards of the Hall probe ar-

range attached to the large face of the sample. The MO pictures are obtained using a Faraday-active ferrite garnet film mounted on top of the superconductor, which is viewed through crossed polarizers in a microscope. Fig. 1 shows the MO image recorded at 4.8K with a magnetic field of 400Oe applied perpendicular to the foil. The flux penetration is seen to advance in finger-like structures producing a ridged landscape, where each ridge has the characteristics of the critical-state with an “inverted V” flux density profile (the MO investigation also showed that the finger structure grows smoothly as the field is increased, and should not be confused with the dendritic structures abruptly appearing during thermal runaways in thin films [14–16]). An array of 11 Hall-sensors (white dots) was mounted along the large central ridge in the landscape, which we regard an optimum location for avalanche observations.

Shown in Fig. 2 are typical data obtained from one of the Hall sensors while a magnetic field perpendicular to the Nb foil was ramped from 0 to 3.5kOe at the rate of $1\text{Oe/s} \pm 0.05\text{Oe/s}$ using a superconducting magnet. The resolution of the micro-Hall probe, which is made from a GaAl/AlGaAs heterostructure, is better than 0.21G, equivalent to one flux quantum ($\Phi_o = 2.1 \times 10^{-15}\text{Tm}^2$) under the probe area. We quantify the Hall signal by the number of vortices (flux quanta) located under the $10 \times 10\text{mm}^2$ sensor area. Although the overall curve appears smooth, the magnified views in the insets clearly show that the amount of flux in a given area varies in distinct steps. This is direct evidence that the vortex penetration evolves by an avalanche-type of dynamics. The individual steps, which we define as avalanche events, have a vertical size ranging from fractions of a flux quantum to more than a hundred vortices. Near 400Oe the main curve makes an upturn, which indicates when the propagating flux front reached the probe position. Above 1kOe the Hall signal grows linearly, corresponding to the Nb foil being fully penetrated. The whole curve follows the prediction of the critical state model for perpendicular geometries [17].

The signals recorded from all the 11 probes were subjected to further statistical analysis. A histogram of the avalanche sizes, taken as the number of magnetic flux quanta in a distinct step, is shown in Fig.3. The data include approximately 200 000 avalanche events observed during several field sweeps up to 3.5kOe repeated under identical external conditions. The number of avalanches, $P(s)$, versus their size is seen to behave as a power-law over two and a half orders of magnitude in s , with a critical exponent of $\tau = 3.0 \pm 0.2$. Note that our total number of avalanche events is about 100 times larger than in previous studies using micro Hall probes [9–11,13], and our distribution function spans more than 6 decades, which is essential for establishing a power-law distribution in this type of systems.

To address the question of robustness, we performed

avalanche statistics at a variety of locations over the sample area. From Fig. 4, where the different probe locations are indicated, one sees e.g. that while all probes in arrangement II are parallel to the same central finger as arrangement I, also avalanches coming from the neighboring “hillside” will contribute. All probes in arrangement III are located parallel to two “competing” fingers, which, due to some degree of anisotropy in the sample, are thicker than those developing from the upper sample edge. A very different location is the one corresponding to Hall probes 1, 2, 3 and 4 on arrangement IV, and probes 5, 6, 7 and 8 on arrangement V (counting from the left), which was also investigated. A remarkable result is that the avalanche size statistics performed on each of the above mentioned groups of probes gave quite good power laws within nearly one and a half decades on the horizontal axis, and with critical exponent τ consistent with the value reported above.

Although the avalanche distribution is universal in SOC models (see, for example, ref. 18), the slope of the flux density is not. Instead, the slope of the flux density varies with the system parameters such as the local density, or strength, of pins. The topography we observe in Fig. 1 is reproducible from run to run, and hence the deviations we observe from a uniform penetration are due to quenched disorder. Nevertheless, the value of the critical exponent τ we measure is the same at all points in the sample, even though the local magnetic topography in the region of the probe varies from point to point. The fact that the exponents found in the present work are all essentially the same is characteristic of the universality expected for SOC. This robustness, together with the power law distribution of avalanche sizes over two and a half decades provides convincing evidence that SOC is a correct description of the penetration of flux into a type II superconductor in the presence of strong disorder.

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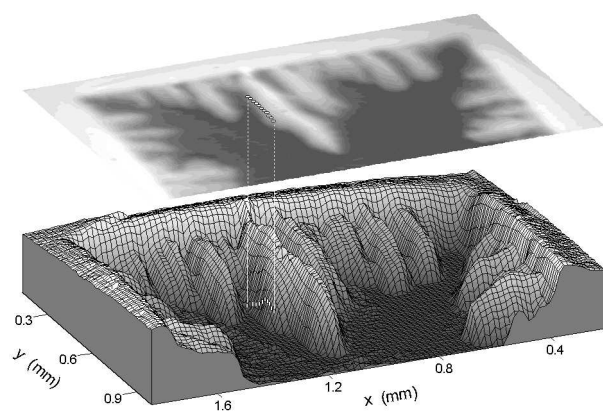
Figure Captions

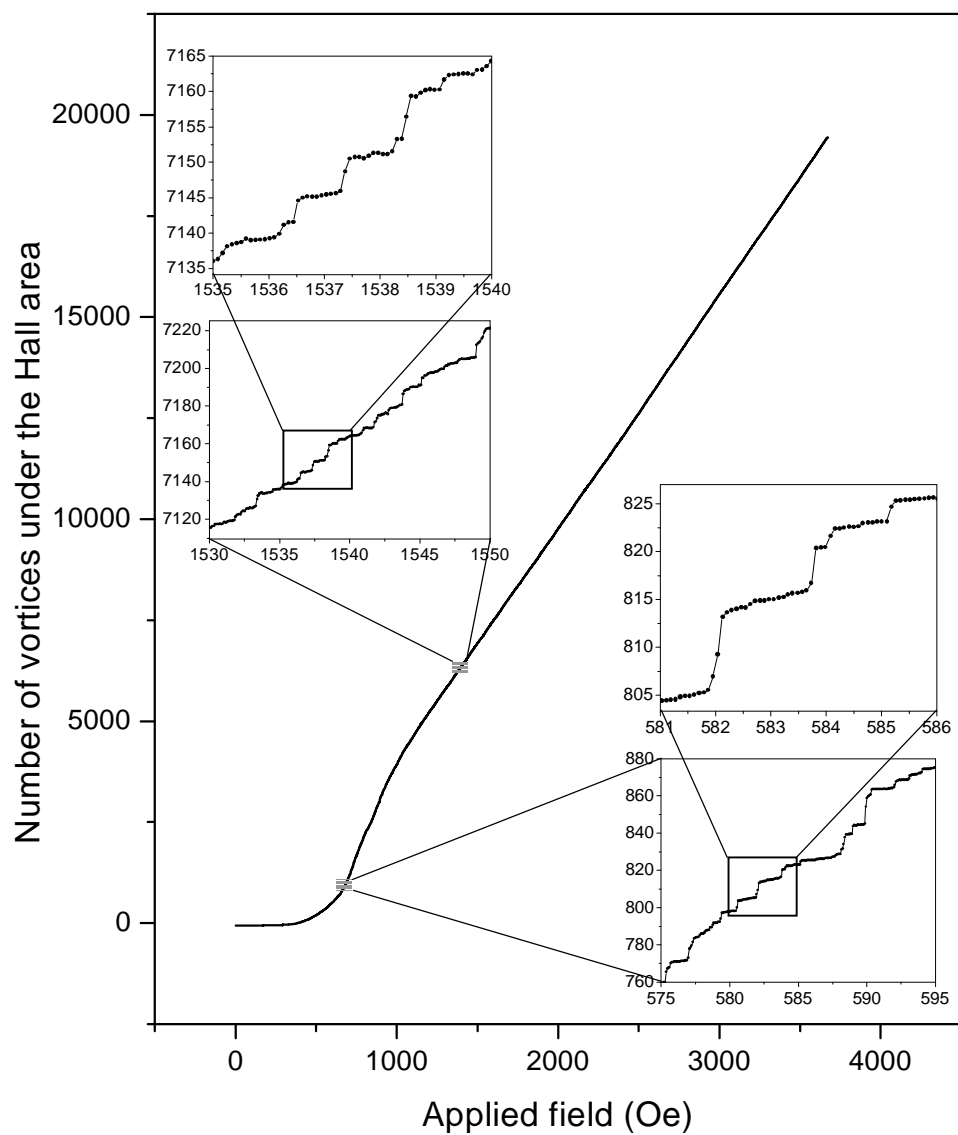
Figure 1 Magnetic landscape of the Nb superconductor. The magneto-optical image (top) shows how the flux penetrates into one half of a $1.5 \times 1.5 \times 0.25 \text{ mm}^3$ Nb foil at a field of 400 Oe applied perpendicular to the sample at $T = 4.8 \text{ K}$. The image brightness represents the local density of the magnetic vortices. The 3D-plot (bottom) of the penetration pattern shows that the magnetic landscape consists of several ridges with smooth slopes, which rise up from the flat Meissner state (flux free) area. Included in the figure is the location of a Hall probe array where each of the 11 probes detects the flux under an area of $10 \times 10 \text{ mm}^2$. As the applied magnetic field increases all the ridges grow gradually on a macroscopic scale, quite similarly to the way sandpiles increase in size when grains are added.

Figure 2 Vortex avalanches seen by a Hall probe during field increase. The main curve was obtained from probe number 4 from the sample edge in Fig. 1, and contains more than 40,000 data points. The insets show zooms in two different field windows revealing distinct steps as a manifestation of avalanche dynamics. The experiment was performed at $T = 4.8 \text{ K}$.

Figure 3 Size distribution of avalanches. The statistics is based on nearly 200 000 avalanche events measured in the Hall probes located as shown in Fig. 1. Steps less than $0.5\Phi_0$ were excluded from the counting of events. The avalanche sizes were exponentially binned, giving equi-distant points in the log-log plot. The data are fitted by the straight line $P(s) \sim s^{-\tau}$, with $\tau = 3.0 \pm 0.2$.

Figure 4 Magneto-optical image of the sample with an overlay showing 5 different locations of the Hall probe array used for supplementary measurements. Location (I) is identical to the one in Fig. 1. The image was taken at 450 Oe and 4.8 K, and the scale bar is 0.2 mm long.





Altshuler_fig2

